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FINAL TECHNICAL REPORT

Project Title: Applied Physics Research for Innovation in Pulsed Power (Grant No.: N00014-90-J-4074)

Principal Investigator: Martin A. Gundersen
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Los Angeles, CA 90089-4048

Research Period: June 1, 1990 - June 30, 1994

Abstract

The program addressed fundamental issues in pulsed power technology, emphasizing new GaAs based solid state switches, and new high power thyratron type switches. Results included demonstration of a fast GaAs-based vertical FET-type switch for power modulator, radar and microwave applications, and development of super-emissive cathode switches. Transition of this research to technology is discussed first, then summaries of some of the recent activity are presented. Technology transitions from the research include initiation of a small business in the area of pulsed power technology, substantial impact on modern high power thyratron technololgy, and impact on the development of solid state devices, including GaAs-based structures. Ongoing work that is related to technology transfer includes development of electron beams for fusion (electron beam ion trap), accelerator and microlithography applications, and development of cathodes with ultra-high emission properties (super-emissive cathode).

Technology Transfer

A small business, Integrated Applied Physics, Inc. (IAP), Torrance CA, was founded for the purpose of bringing to the market high power thyratron-type switches based on super-emissive cathodes, and high power modulators based on these and related switches. The switches fall into the category of "pseudospark" switches, and include the back-lighted thyratron (BLT), and they conduct higher current than comparable thyratrons, and have a number of other attractive properties. SDI supported research that determined the physics underlying the super-emissive process, and the invention of the BLT. This company addresses a technology (high power, short pulse switching) that is not currently emphasized in the U.S., but is under active development in other countries. For example, in Europe the switch has been under development at Siemens (Germany), Thomson

(France), ONERA (France), EEV (Britain), and in Russia (Ryzan). There is little open information about future planned commercialization by companies in the U.S., possibly for proprietary reasons, but there is apparently only limited investigation by EG&G and ITT, the major thyratron companies. Commercial versions of the switch are available from Russia, and are anticipated shortly from at least EEV, and possibly Siemens, for applications that include environmental (pulsed percipitators for flue gas and exhaust treatment), the operation of excimer lasers, and medical kidney stone treatment (lithotripters). In Europe, for example, a consortium of Universities in France, England, Italy and Germany is planning a test of a high voltage pseudospark for reduction of power plant pollution. IAP has been investigating this application under support from a DOE Phase II SBIR grant. A discussion of the current status and marketing issues can be provided.

In other areas, a student working on GaAs vertical FETs for high power has recently been hired by Motorola to work on design of new generation GaAs devices, and an electron beam produced by the BLT is under development at USC for sub-micron microlithography of semiconductor chips. The electron beam is robust, and much simpler to generate and control than X-ray sources. The present work will determine the feasibility of producing feature sizes of approximately 0.1 microns.

High Power Thyratron-Type Switches (BLT and Pseudospark)

The super-emissive cathode switch, known as a pseudospark or a back-lighted thyratron (BLT), *has different, sequential phases of operation including:* (i) ignition, (ii) a transient high-voltage, relatively low-current phase (hollow cathode discharge), and (iii) a high-current phase (conducting or super-emissive phase)[1]. The intermediate hollow cathode phase is under investigation for electron and ion beam applications. The final, high-current phase, provides high rates of current rise time (up to 10^{12} A/s) and high peak current (1-100 kA), which combined with the simple design is important for pulsed power applications. In the BLT the first electrons are photoelectrons released by UV light which is provided by a flash lamp (ignition phase)[2]. Here, the photoelectrons are multiplied by a hollow cathode effect[3], and a plasma is formed by inelastic collisions with the background gas (H_2, He, Ar, at a few Pascal). Computer simulations predict[4] that the anode potential moves toward the cathode during the hollow cathode phase and secondary electron emission mostly due to ions provides electron current and leads to a transition to the high-current phase. During this research period evidence for a microscopic cathode spot mechanism was developed including: cathode metal vapor detected in pseudospark switch[5], the erosion rate of cathode under certain conditions

($\approx 10^{-5}$g/C[6]), the cathode surface morphology[7], and cathode spots detected directly in the high current phase[8,9]. A model of cathode electron emission for several high-current phases of pseudospark operation was developed. The physics of this model provides insight into the relationship between glow and arc discharges, and provides information related to life limiting erosion related to the cathode emission process.

High-Voltage Recessed-Gate GaAs Field Effect Transistors

Development of low on-resistance, high speed GaAs-based static induction transistors (SIT's) by the group at USC for high power switching applications was undertaken, and work on a advanced gate structures with large blocking voltage was conducted. The device design parameters of a "buried gate" structure are voltage blocking capability of 200-400 volts (blocking gain >10), on-state conduction current of ~1A (R_{sp}<10 mΩ.cm^2), and switching speed of <50 ns. The design parameters of "recessed-diffused junction gate" SITs are in turn voltage blocking capability of 150 volts (R_{sp}~1 mΩ.cm^2, blocking gain >25) and 300 volts (R_{sp}~3 mΩ.cm^2, blocking gain >75), respectively, on-state conduction current of ~1A, and switching speed of < 50 ns. The large voltage gain in the "recessed-diffused junction gate" SIT results in a low gate drive power requirement. Applications include automotive electronics, DC motor control, solid state DC relays, VHF telecommunication, resonant switched-mode power supplies, and spacecraft power conditioning systems.

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1. For a review of various properties and applications of pseudosparks see, for example, M. A. Gundersen and G. Schaefer, Eds., *The Physics and Application of Pseudosparks*, NATO ASI Series B: Physics vol. 219 (Plenum, New York, 1990).
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5. G. Lins and W. Hartmann, "Metal vapor densities in pseudospark switches with tantalium carbide cathodes", J.Phys. D: Appl. Phys., Vol. 26, pp. 2154-2158, (1993)

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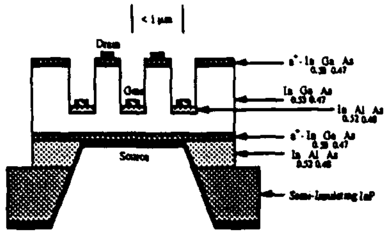
8. M. Stetter, "The phenomenon Pseudospark", WE-Heraeus Seminar, Gaseous and Electrode Phenomena in Diffuse High Current Density Discharges, (Bad-Honnef, 1-6 November 1992, Germany, unpublished)

9. R. Tkotz, A. Linsenmeyewr, P Felsner et al., "Investigation of cathode spot formations in a high power pseudospark switch" ibid.

Efficient, Repetitive Pulsed Power



Concept for GaAs SIT

Research

Power conditioning, microwave sources, motors and vehicles,

- **Miniaturize**
- **High Speed**
- **Efficiency**
- **Life**
- **High temperature operation**

Approach

Develop new materials for devices,

- **GaAs, SiC, diamond**

Research needed

- **Contacts**
- **Doping**
- **Material quality**
- **Fabrication issues**

Applications

Miniaturize radar

- **On-board missile, low weight**

UWB radar

Optoelectronic devices

Motor control, electric vehicles

Satellite

International competition

Efficiency

<u>*Efficient, repetitive*</u> pulsed power is deliberately emphasized.

Efficiency is critical when you create a *fast rising, pulse.* When you turn it on *fast,* rather than using DC or a sine wave (AC). It would be much better for many applications if you could use a fast pulse, that you can turn on without wasting energy, instead of a long pulse.

It is at present hard to turn on power pulses quickly (in the ≈10ns regime, for example) without wasting energy, or damaging the switch. This affects life, range of appliations, many issues.

For most applications, this is the arena--developing more efficient pulsed power systems that operate at higher repetition rates. For example, in satellites, on board a ship, in a missile, for air pollution, water pollution, radar, lasers, motors, vehicles, the problem is to produce *efficient* repetitive pulsed power.

Repetitive Pulsed Power is a Critical Technology

- **Listed as a DoD critical technology**
- **Under active development in other countries for military applications**
  - **Very aggressive development of pseudospark in Europe**
  - **Japan, Europe, Russia developing solid state**
- **Applications: satellites, HPM, radar, missiles, lasers, electric motors and vehicles, power control**
  - **In addition, industrial, environmental appliactions with large potential markets**
- **Dropped by agencies**

Pulsed Power Defense Applications

- **Bi-Static radar**
  - **Separation of radar transmitter from ship requires light pulsed power**
  - **Less on-ship damage, target away from ship**
- **Patriot-type**
  - **≈100 kW to produce ≈30kW radar to acquire target before launching**
  - **To increase field by 10, increase radar power by 10^3–<u>10MW</u>! Need compact, light, efficient pulse generator**
- **Pulse generator on cruise missile**
  - **EMP, generate behind enemy lines**
- **Electric guns to shoot down cruise**
- **Electric launch of aircraft on carrier**
  - **≈60 MJ in≈2sec**
  - **Launch downwind capability**

Research Needs

- SiC, diamond, GaAs, InP, ternary and quaternary III-V promise high voltage, speed, efficiency
- Growth, Fabrication of Material
  - Defect issues critical for high power, particularly in new materials
  - Electrical contacts limit power application
  - Growth facilities needed for power-oriented SiC, GaAs
    - » Specialized growth for power–Thick and thin–High voltage needs thick, high current needs thin
- Device issues needing R&D
  - Doping of new materials requires much R&D
  - New devices with on-board logic and communication, heterostructure devices
- Energy storage
  - Capacitors- 1J/gm for long life
  - Batteries- operational issues for high energy storage, such as NaS
- Inductive energy storage
  - Inductors
  - Opening switches
- Optimization, fabrication of power modulators

Additional Applications for Repetitive, Efficient Pulsed Power

- **Electric vehicles and Electric motors**

  •many applications improve electrical efficiency if use higher voltage components (power loss is IR, higher V means lower I)

- **Power conversion**

  Solid state voltage sources can switch power, generate and absorb reactive power, filter, without reactive components

- **Medical applications**
- **Many environmental applications**

  •Ground water pollution

  •Air quality

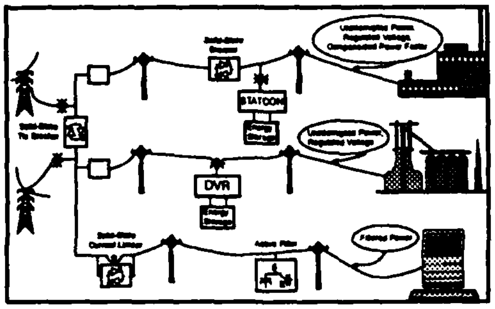
  •Reduction of toxic waste

  •Zebra mussel proliferation

Custom Power

Tremendous cost savings, improvements in productivity with better power control (≈1/4 US grid energy lost in motor control)

- **Problem: High power components to control:**
  - **Voltage variation**
  - **Voltage transients**
  - **Reactive power**
  - **Interuptions**
  - **Harmonics**
- **Power components for**
  - **Voltage regulation**
  - **Voltage restoration**
  - **Uninterrupted power**
  - **Reactive power compensation**
  - **Harmonic control**



Electric Vehicle Applications

Japan's MITI to build 200,000 by year 2000

Estimated sales 1.4 million in 2005 (Autofacts Inc.)

California law requires 10% zero emissions by 2005 (estimate >200,000 vehicles)

Drive Requirements
- **Constant torque mode**
- **Constant horsepower mode**
- **Switching frequency**
- **Efficiency**

Switch Requirements
- **High temperature**
- **≈ 1 kV, 100-1000A**
- **Low on-state voltage**
- **fast switching time (increases efficiency)**

Radar Transmitter

- On-board missile radar
- Devices requiring R&D
  - SIT
  - e-beam controlled semiconductor switches
  - Opto-thyristor
  - Super-emissive cathode switches
- Materials requiring R&D
  - Near term: GaAs, InP
  - Longer term: SiC, ternary/quaternary III-V, diamond
- Key issues
  - Forward drop, life, radiation hard, high temperature, speed

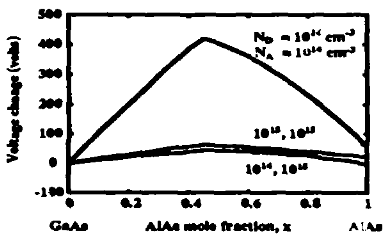
Current Status

- Best available technology either has slow turn-on with long life (solid state), or fast turn-on with short life (spark gap—power dissipated while turning on and operating), is rep-rate limited, or other
- Si dominates, >50kHz rep rate, but slow turn on
- If develop new materials (GaAs, SiC, diamond), can improve
  - Speed–fast turn-on (current rise-rate–presently ≈20kV/μsec)
  - high voltage (>5-10kV)
  - EFFICIENCY (higher mobility<=>lower forward drop<=> less energy dissipation)
  - Life (particularly in comparison with gas, hard-tube technology)

Power Device Comparison

Device	Blocking voltage, peak current	Turn on/ Turn off times	Forward drop (Volts) ($100A/cm^2$)	Comments
Silicon controlled thyristor (SCR)	6.5kV, 80kA	10-100 μsec/ No turn off	1.2	Highest power, can't turn off, long recovery time
Gate turn-off thyristor (GTO)	6kV, 4kA	5-10 μs/ 10-100μs	1.2-1.6	Can turn off, difficult to use
Field effect transistor (FET)	~600V, 250A	1-10ns/ 1-10ns	5-10	Very fast, limited by on state resistance, must stack for high voltage
Insulated gate bipolar transistor (IGBT)	1.7kV, 600A	<1μs/ 2-6μs	~3	Combines FET with higher power, but limited voltage
Mos controlled thyristor (MCT)	700V, 120A	<1μs/ 2-6μs	1.2-1.7	New, like IGBT, but more efficient, with slower turn-off. Developing higher V
Research area: Silicon Carbide (research goal)	Potentially high	not known, fast	not yet known	High thermal conductivity, high temp (400C), Figure of merit 90 to 2400 better than Si
Research area: Diamond	Large bandgap, should be extremely high	ns/ns, possibly faster	low if bulk mobility realized in switch	Very fast, very high voltage, very high temp. Figure of merit 10^3 to 10^8 >Si
Research area: GaAs	High hold off in thin device	ns/ns	high mobility in linear mode, expect low drop	High operating temperature, high mobility, high stand-off, can integrated with optical control

Understanding of Solid State Processes is Needed



Hold-off vs Al/Ga alloy concentration

OBJECTIVE

- Find theoretical limits
- Modeling support for all semiconductor efforts
- Determine whether III-V, Si, C (diamond), II-VI are practical materials for SDIO pulsed power switching
- Surface breakdown mechanisms

APPROACH

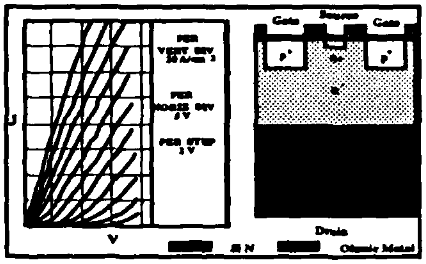
- Microscopic, quantitative model
- Model field-related transport using band structure, defects
- Model field-dependent surface transport processes
- Calculate ionization rates, breakdown for the various materials

PAYOFF

Understand

- Which III-V, II-VI, other materials to develop as devices
- High current behavior (such as lock-on)
- Surface flashover fundamental limits

USC Development of GaAs Static Induction Transistor

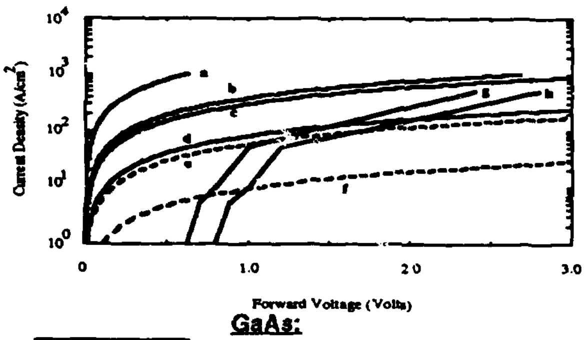


- The GaAs-based SIT is a fast power electronics opening and closing switch
- Under development at USC (P. Hadizad + M.G.) in collaboration with MOCVD group (P.D. Dapkus) and fast device group at UCLA (H. Fetterman)

- **Advantages for efficient motor control, vehicles, radar, satellite communications, other pulsed power**
- **High voltage, more efficient operation**
  - lower forward drop
  - less device heating
- **High temperature operation**

A high voltage optoelectronic GaAs static induction transistor," P. Hadizad, J. H. Hur, H. Zhao, K. Kaviani, M. A. Gundersen, and H. R. Fetterman, IEEE Elec. Dev. Lett. (1993)

Current Density-Voltage Characteristics Majority and Minority Carrier Devices



GaAs has significant advantages in power dissipation, speed

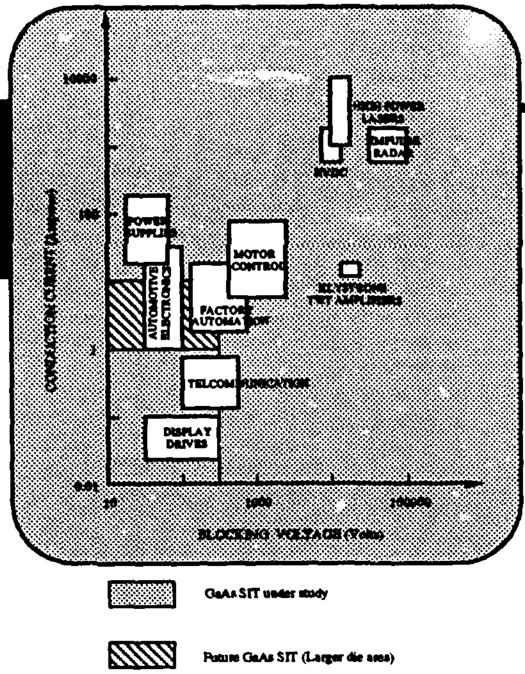
a) 200 V GaAs FET
b) 400 V GaAs FET
c) 200 V Si FET
d) 800 V GaAs FET
e) 400 V Si FET
f) 800 V Si FET

g) 250 V PIN
h) 800 V PIN

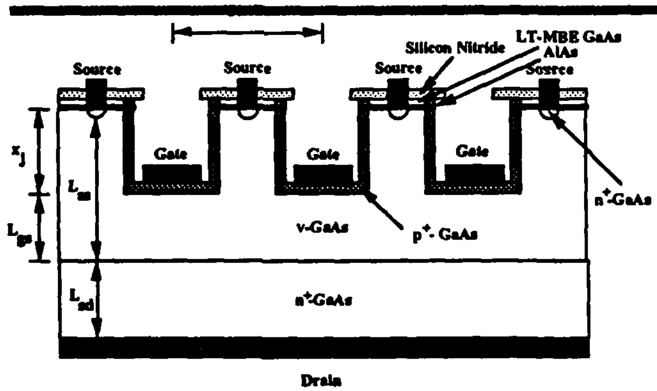
GaAs:

. High electron drift mobility
  Low forward voltage drop and
  fast switching speed in majority carrier devices

. Large energy gap
  High breakdown voltage
  High tolerance to temperature and radiation



Recessed-Diffused Gate GaAs SIT



- Recessed-diffused gate geometry
- New surface passivation structure

- Low forward voltage drop
- High blocking gain (Low power gate drive)
- Fast switching speed
- High temperature and radiation tolerance

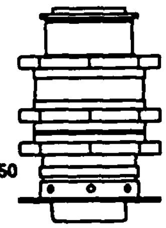
Size, Weight Breakthrough

Pseudospark, BLT demontrated performance between spark-gap, thyratron
Thyratron...lower current, but life advantage
Spark gap...comparable or higher current, shorter life, lower repetition rate

BLT Weight, performance comparison with thyratrons

Type	Resv. Power (res)	Weight	Max Current	Diam
1802	110 W	20 gr	~2kA	4 "
HY 5	190 W	50 gr	5-10kA	4.5 "
HY 7	1660 W	400 gr	40 kA	7"
BLT	2 W	2 gr	≥40 kA	1.75 "

IAPI BLT 250



EEV CX 1700

Faster di/dt, 1000X less housekeeping power, higher current, voltage, incl. housekeep. 100X wt reduction (cathode also much smaller), < 1/10 volume

BLT, pseudospark research
- **extend life beyond 100-2000 kCoul**
- **stability of emission over switch life**
- **Physics of emission is related to performance**

Foreign Interest in Pseudospark, BLT

The Pseudospark and BLT, which have military applications, are under active development in the following countries.

Japan: Hitachi, Tokyo Institute of Technology, Mitsubishi, Kyoto

Soviet Union: V.I. Vizir (Tomsk), Bushuev (Sov. Phys. Tech. Phys. Dec 90), doing research, Ryzan (leading Russian thyratron company) makes commercial version

France: Thomson CSF developing commercial version, Toulouse, Orsay, ISL, ONERA conducting development

Germany: Erlangen, Aachen, Siemens (Siemens has version that can be sold, if they decide). Pseudospark is main topic of 1994 German Physical Society Plasma Physics Meeting. Several organizations are developing multiple aperture switches for applications including flash X-ray sources for sub-micron IC fabrication and copper vapor lasers

Italy: Italian National Electricity Board

China: Beijing, Chang Sha